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Quarterly Update Carbon Sequestration Program

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QUATERLY UPDATE

Carbon Sequestration Program

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WORK PERFORMED UNDER AGREEMENT

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Executive Summary

Ensuring that geologic CO_2 storage is safe and effective will require site-specific quantitative risk assessment, which combines performance assessment of a storage site (i.e., prediction of the fate and impact of the stored CO_2) with an assessment of potential consequences of concern (e.g., environmental, health, economic). DOE's Office of Fossil Energy's Carbon Sequestration Program involves components spanning the range from applied research at the laboratory through pilot scale (the Core R&D Program) to Demonstration and Deployment (e.g., the Regional Carbon Sequestration Partnerships, international engagement and other commercial opportunities). As the state of geologic sequestration technology approaches commercial viability, risk assessment methodologies must be developed and validated.

Task 1.0 of this effort is focused on the development and implementation of the National CCS Risk Assessment Program, formed to address the critical questions in risk related to geologic carbon sequestration. This work will be done in conjunction with the other National Laboratory partners that have participated in the working group.

- Risk assessment white papers on 6 technical areas have been submitted to NETL.
- Preliminary risk profiles for carbon storage are being constructed
- Field sites have been identified
- National Laboratory specific research has started

Task 2.0 is focused on establishing the potential for using brine pressurized by Carbon Capture and Storage (CCS) operations in saline formations as the feedstock for desalination and water treatment technologies including nanofiltration (NF) and reverse osmosis (RO). This method uses the energy required to inject the carbon dioxide to provide all or part of the inlet pressure for the desalination system. Residual brine would be reinjected into the formation at net volume reduction. This process and improves the sequestration system by providing additional storage space (capacity) in the aquifer as well as low-cost fresh water to offset costs or operational water needs. It also reduces operational risks by relieving long-term pressure growth in the aquifer.

- We began modifying the EQ3/6 software to accurately capture the RO and NF processes
- The USGS Produced Waters database was extended to better determine the abundance of total dissolved solutes (TDS) in saline formation waters in the United States
- Modeled brine generation as a means to manage pressure within the storage reservoir

Task 3.0 is a comprehensive multi-disciplinary effort that addresses two fundamental challenges to successful geologic CO2 isolation at In Salah that are equally relevant to the broad range of CO2 storage scenarios; 1) Quantify CO2 plume migration and sequestration partitioning among distinct trapping mechanisms within dynamic, complex permeability fields characterized by multi-scale heterogeneity—emphasizing assessment of coupled processes that may lead to early CO2 breakthrough at production wells. 2) Evaluate geomechanical response and potential supra-reservoir leakage, through faults, fractures and well bores, which may ultimately reach the surface. Successfully addressing these challenges requires quantitatively representing injection-triggered hydraulic, geochemical and mechanical processes within reservoir, cap-rock, and well-bore environments. Such representation requires modeling approaches that explicitly integrate these processes. The research augments and advances ISP's earlier in-house reservoir simulation work by adding explicit account of permeability evolution due to injection-triggered geomechanical and geochemical processes, which together may lead to significant modification—enhancement or degradation—of reservoir, caprock, and well-bore integrity.

- LLNL completed experimental geochemistry studies involving In Salah reservoir sandstone and shale samples and simulated wellbore cement. The experimental studies were interpreted using geochemical modeling to identify candidate reactive mineral phases and quantify associated dissolution kinetics to inform reactive transport modeling. This work enabled LLNL to meet two progress milestones pertaining to completion of initial wellbore integrity simulations and the integration of batch experiments with reactive transport modeling.

- LLNL constructed a revised CO_2 injection model, based on an updated permeability and porosity realization for the reservoir and calibrated to wellbore bottom hole pressure data, to predict the distribution of CO_2 saturation, fluid pressure, and corresponding land surface deformation.
- LLNL scientists participated in the In Salah Science Advisory Board review meeting in Cambourne, U.K, in February 2010, presenting summaries of accomplishments in coupled flow and geomechanical modeling as well as geochemistry experiments and reactive transport modeling.

In Task 4.0 LLNL will work in collaboration with the DOE-FE, NETL and the West Virginia University to provide technical support for a potential carbon capture and storage (CCS) project for Shenhua Direct Coal Liquefaction (DLC), China. The work includes assessment and identification of CCS potential within the Ordos Basin, an estimate of the fate of stored CO2 using reactive transport simulators and geologic models based on available literature, and consideration of monitoring and verification needs and potential technologies. LLNL will also contribute to topical reports requested by DOE and Shenhua DLC.

- Meeting with LLNL, DOE, University of West Virginia and Shenhua DLC in China resulted in the transfer of technical data for work in the next quarter

In Task 5.0, LLNL will study the role of injection-induced mechanical deformation and directed sea-floor monitoring at the Snohvit CO_2 storage project. LLNL will study two components relevant to storage effectiveness and operational success: the geomechanical effects of injection on rock deformation and fault leakage hazards, and guidance on developing a monitoring program focused on possible migration of CO_2 and brines to the seafloor. Results from this work will enhance the predictive capability of field performance models, provide a new basis for interpretation of geophysical and operational data at Snohvit, and provide support for the creation of appropriate regulations and monitoring schemes for sub-sea geological storage of CO_2.

- Hired Dr. Laura Chiaramonte (Ph.D. Stanford)
- Meet with LLNL and StatoilHydro to arrange transfer of technical data for work in the next quarter

Current Status

Technical Status

1.0 Task 1.0: National Risk Assessment Project Collaborative Research

LLNL has been working with LANL, LBNL, NETL and PNNL to enhance the nation's capabilities for science-based risk assessment for geologic carbon sequestration. The national laboratory effort addresses pressing research gaps which are limiting the advancement of geologic sequestration and our ability to perform risk assessment to ensure that CO_2 storage is safe and long-term. Research tasks are organized around monitoring for risk assessment, well integrity, leakage through natural systems, groundwater impacts, and systems modeling for risk assessment. Each working group has representation from each national laboratory and projects are collaborative between labs. Because of the nature of geologic sequestration, there is some overlap between the five research areas, and some work is common to more than one task. Work in the systems area integrates the information and ideas from all of the other areas.

1.1 Six white papers addressing research gaps for geologic carbon storage have been submitted to George Guthrie and Grant Bromhal at National Energy and Technology Laboratory for final review and publication. Topic areas included research gaps for monitoring for risk assessment, wellbore integrity, leakage through natural systems, geomechanics, groundwater impacts, and systems modeling for risk assessment.

1.2 An overarching white paper has been drafted to describe the major goals of NRAP (see attachment "NRAPwhitepaperR3"). All research conducted in the project feeds into risk assessment calculations that reduce uncertainty for geologic carbon storage over time. Detailed work breakdown structures for the Project Management Plan have been submitted to George Guthrie and Grant Bromhal by the organizational leads of each of the five theme areas. These planning documents will be further refined to be consistent with risk assessment calculations described in "NRAPwhitepaperR3" in July 2010.

1.3-7.2 Identification of qualities needed in natural analog or field site

About 30 members of the NRAP team from all five national laboratories met in Lawrence Livermore National Laboratory in January 2010 to identify the qualities needed in natural analog and field sites to address research needs for risks associated with geologic carbon storage. Based on this list the theme groups proposed about 15 different sites for study. This study has been narrowed to the following sites.

1. EPRI controlled release site – groundwater leakage
2. Rocky Mountain Oil Testing Center (RMOTC) – wellbore integrity, natural seal integrity, monitoring, groundwater leakage
3. Cranfield Mississippi – wellbore integrity
4. Springerville Natural Analog – groundwater, natural seal integrity
5. University of Calgary, Leakage Test Site – groundwater, monitoring

Additional natural analog sites are still being considered. Research at each of these field sites is pending administrative controls and future funding by the DOE.

1.3 Monitoring for risk assessment: LLNL specific research

LLNL is using the LLNL stochastic engine to map the spatial distribution of CO_2 within the reservoir using cross-well seismic tomography and ERT data from the Cranfield site to constrain the uncertainty associated with spatial distribution of the CO_2 plume. Our new joint inversion of both seismic and ERT data takes advantage of prior information such as geology, reservoir, temperature and injection volume, uses two very different physical detection mechanisms, and provides a rigorous estimate of model uncertainties for risk assessment. The joint inversion of these two data sets will reduce solution uncertainty. Robust estimates of the uncertainties associated with CO_2 distribution are essential when assessing CO_2 sequestration leakage risk.

Currently, LLNL has a full spectrum of ERT capabilities in house. We are incorporating modules that will compute cross-well seismic travel time (i.e., FMeikonal module of a Stanford Exploration Project (SEP) seismic data processing library). When the necessary modifications are completed, we will jointly invert the seismic and ERT data collected at Cranfield, and provide estimates of the solution uncertainty. This work will help the MVA group within NRAP to evaluate the usefulness of these results as input to risk assessment calculations. Our current work at Weyburn (Ramirez et al, 2010) and Cranfield (Carrigan et al., 2010) will bring synergy to this CO_2 MVA project.

1.4 Wellbore Integrity: LLNL specific research

Wellbore integrity research has just begun. Research will focus on incorporating reactive transport simulations of wellbore carbonation and concurrent changes in porosity and permeability to flux rates in the wellbore environment. One of the biggest unknowns is the molecular volume to the calcium silica hydrate gels that form in wellbore cements prior to alteration by CO_2-rich brines.

1.5 Pathways Through Natural Systems: LLNL specific research

At LLNL we use quantitative tools developed in-house to answer the fundamental components associated with leakage through natural pathways, such as the properties of the natural pathway and the volume and rate of fluid movement through the natural pathway out of the target sequestration reservoir. Towards this effort, we analyzing injection-induced deformation, that can lead to CO_2 migration through these natural pathways, following a two scale/modeling approach:

The first approach is to generate a continuum, implicit, fully coupled hydromechanical model to analyze injection-induced deformation for target reservoirs (Figure 1). This tight coupling is particularly crucial for fractured sites where permeability is very sensitive to the evolving stress condition. To-date we have applied this method to study the potential for fault activation and consequent potential for fluid migration along preexisting faults at the In Salah CO_2 sequestration project (White, 2010). As a result of the pressure increase, a small fault is reactivated and therefore permeable for fluid flow, where the other two faults are impermeable. These results are in agreement with previously modeling results from NUFT and LDEC (Morris et al, in press).

The second approach is to generate a discrete, explicit, loosely coupled model to analyze discrete faults/fracture evolution, permeability changes, and induced seismicity for target reservoirs. This approach targets local scale understanding of the injection induced deformation and it is used to calibrate reservoir scale simulations. A comparison of the two continuum and discrete models is shown in Figure 2 against analytical solution show that these numerical approach can give better understanding of full fault behavior.

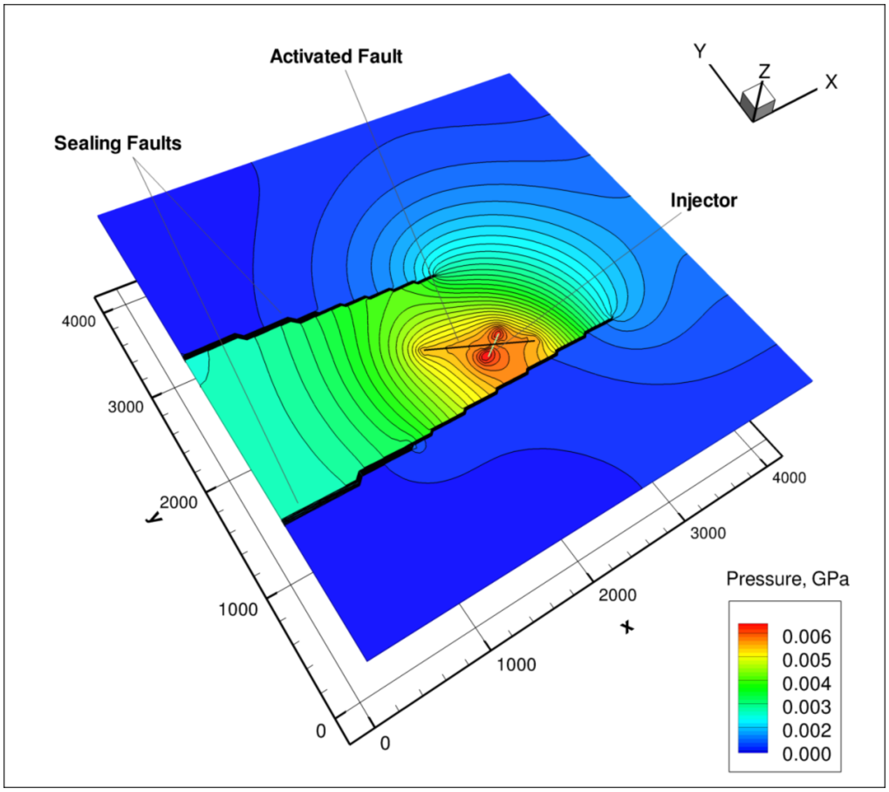


Figure 1.- Fully-coupled single-phase simulation of CO_2 injection through a horizontal injector pressurizing nearby-faults (White, 2010).

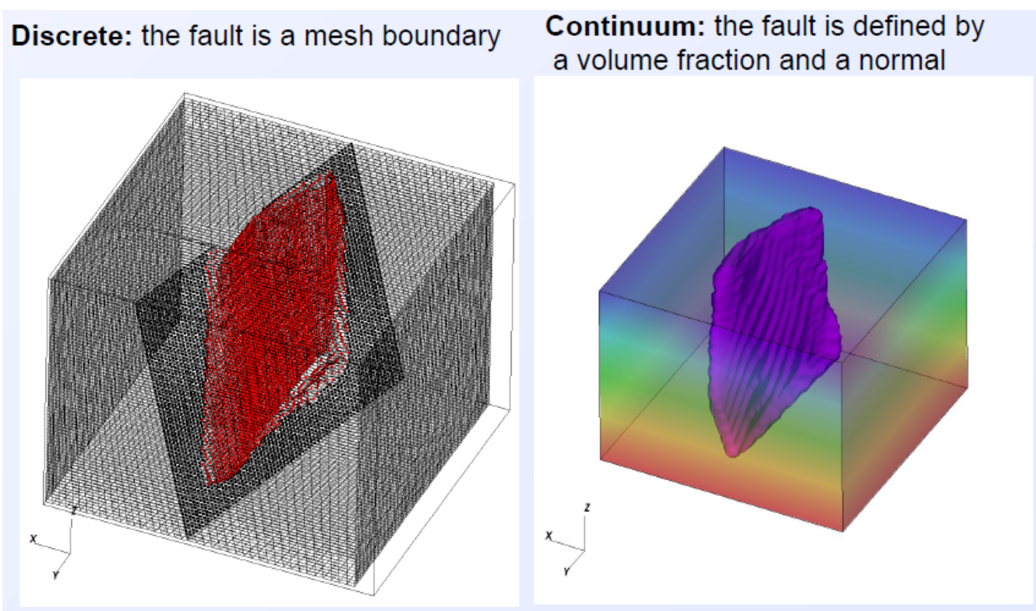


Figure 2.- Continuum versus discrete fault representation using GEODYN-L LLNL's code (Vorobiev et al., 2009).

1.6 Groundwater Impacts, LLNL specific research

LLNL has measured the release of Ni, Pb, Cd, Cr, and Cu when CO_2-rich brines react with sandstone, shale, and cement at reservoir conditions. All five of these trace elements will compromise groundwater quality and will pose a health risk if their concentrations exceed the EPA's maximum concentration levels. These results show that Ni and Pb are key elements of concern because their concentrations exceed the EPA's maximum concentration levels even at steady-state conditions. Cd and Cr do not appear to be a long-term impact, because concentrations tend toward the EPA's maximum concentration levels at steady-state. Cu concentrations are much lower than the EPA's maximum concentration levels. LLNL will continue these experiments with reservoir and caprock materials geologic carbon storage projects. We have carbonate and evaporate samples from Weyburn-Midale field, and sandstone and shale samples from the Illinois Basin.

Results will be incorporated into the Systems Risk Analysis in collaboration with this group.

1.7 Systems Modeling – LLNL specific research

LLNL's technical work has helped develop a framework for the calculation of meaningful risk profiles that can assimilate science-based information provided by the other NRAP research groups. This entailed several considerations, including: understanding the nature of plausible risks, their potential measures, and objectives for their management; a tractable approach for including relevant physical processes in a calculus for quantifying risks; considerations on how to treat uncertainties, both aleatoric and epistemic; and the trial generation of sample risk calculations to explicate the methods and to foster technical interchanges with the other NRAP research groups.

The risk issues to be considered must articulate the idea that the perceived hazard is reasonable and can be evaluated in a clear and physically meaningful context. The research has identified two basic classes of hazard: leakage related; and induced seismicity. The leakage risks are manifested as impacts on groundwater quality (such as pH or total dissolved solids) and release of CO2 into the surrounding environs including occupied structures. The overall leakage is also a performance issue affecting the 'permanence policy' of 99% containment. The induced seismicity risk is manifested as ground-based acceleration that can impact surface structures and activities. The seismic events could also feedback on the creation of additional leakage pathways.

Sample risk calculations have been considered to help refine thinking about the risk analysis framework and risk-related metrics and profiles. The initial emphasis is to calculate "preliminary" risk profiles for at least the leakage related metrics. The first step is to put together a hypothetical field site that will have modules (such as a sequestration reservoir, cap seals, wells, faults, and a shallow aquifer) that are representative of some of the sites the broader group has considered, like SACROC and Kimberlina. The major calculation components are a reservoir model that predicts pressure and saturation at the caprock interface; wellbore flow models to calculate leakage rates (with stochastic distributions of wellbore locations); and functions to describe movement of fluids in to a shallow aquifer. LLNL is particularly suited to contribute to the modeling of the induced seismicity effects due to pressure forces at the reservoir/caprock interface. This information also feeds back to considerations of additional leakage pathway effects. The leakage fluxes will have to be modeled in sufficient detail to provide spatial and temporal dependencies; dependencies on injection scenarios and parameters; CO2 profiles to support MVA activities; and to develop useful probabilistic risk profiles. Risk profiles of interest include pdf-based 'return-level mappings' that are curves explicating the probability of exceeding various CO2 concentration thresholds as a function of time at selected risk receptor locations (e.g., aquifer locations or atmospheric release points).

2.0 Task 2: Fresh Water Generation from Aquifer-Pressured Carbon Storage

2.1 Brine Treatability Modeling and Analysis

2.1.1. Brine Treatment Modeling and Analysis

We began modifying the EQ3/6 code to more accurately model the reverse osmosis (RO) and nano filtration (NF) processes by incorporating equations to describe the solution rejection process (rejection coefficient model). Our previous modeling produced "pure" water. The new modeling will account for the fact that dissolved solutes will partially migrate through to the fresh water. This is particularly critical for NF, which allows a substantial fraction of the monovalent ions to pass through the membrane.

A draft of the paper "Brine management strategies for reducing the risk of geological sequestration of carbon dioxide" was completed. The paper is under internal review and will be submitted for publication to the International Journal of Greenhouse Gas Control. A second draft paper describing RO modeling applied to subsurface brines is being prepared for submission to the journal *Desalination*. A third draft paper describing a more extensive analysis of the USGS Produced Waters Database and the NETL Rocky Mountain Basins Produced Waters Database is in preparation. The purpose of this paper is to provide more information that will be useful in future selection of sites and target reservoirs in saline water formations, as well as to help define brine compositions for additional modeling this FY. We have previously categorized waters by salinity expressed as total dissolved solutes (TDS). Waters with TDS in the range 0-10,000 mg/L are presently excluded by regulation from CCS activities. Waters with TDS in the range 10,000-40,000 mg/L are considered prime targets for brine extraction and treatment. Waters with TDS in the range 40,000-85,000 mg/L are treatable by conventional to somewhat less conventional means (NF or multi-stage RO). Waters with TDS in the range 85,000-300,000 mg/L require unconventional treatment, and difficulty and cost rise with increasing TDS level. Waters with TDS greater than 300,000 mg/L are probably untreatable by any foreseen technology.

In total we now have results covering CA, CO, IL, KS, LA, MS, MT, ND, NM, OK, TX, UT, WY, and the aggregate Rocky Mountain Basins. MS and IL represent the only two states where attractive target water (10,000-85,000 mg/L TDS) seems to be scarce. It is clear that west of the Mississippi River, attractive target water is abundant, though the level of abundance varies from state to state. East of the Mississippi, the picture is not clear, mainly because the USGS Produced Waters Database has relatively few data in the region (MS and IL are the only two "eastern" states with fairly abundant data). LA, which straddles the Mississippi River, occupies a somewhat intermediate position in terms of attractive target water abundance. In eastern states with little coverage (most of them), one might reasonably expect that a low abundance of attractive target water might correlate with the abundance of subsurface salt deposits (for which data should be available).

Subsurface waters in Colorado appear to be the least saline of any state for which an abundance of data exists. The prime target range of 10,000-40,000 mg/L is more abundant at greater depth. At lesser depth, waters of TDS ≤ 10,000 mg/L are more abundant, although waters in the prime target range remain abundant. For California, there is a major abundance of water in the 10,000-40,000 mg/L TDS range. A caveat, however, is that the data are primarily from the southern part of the state. For Mississippi, most of the water has TDS in the 85,000-300,000 mg/L range. The abundance of water in the attractive TDS ranges is quite small. For Illinois, most of the water has TDS in the 85,000-300,000 mg/L range, similar to the waters from Mississippi.

Task 2.1.2 Experimental Testing:

A contract is being put into place to carry out desalination tests of brines from field sites. The tests will involve either transporting site water to a facility for testing, or carrying out the testing on site. The testing will involve 10s to 100s of gallons of brines. We have identified Membrane Development Specialists (MDS) as the preferred contractor and are negotiating a sole-source contract with Larry Lein, Managing Director of MDS.

Task 2.1.3 Cost Estimation:

No activity this quarter. This is expected, per the schedule.

Task 2.1 Reservoir Pressure Management:

We conducted a model study, using the NUFT reactive flow and transport code (Nitao, 1998), to examine the implications of net brine extraction on pressure management, CO_2 plume, and brine migration. We developed a 2-D radially symmetric model of a saline 250-m-thick CO_2 storage aquifer, which is similar to that developed by Zhou et al. (2008), with the top of the aquifer located 1200 m below the water table, and which is bounded by 60-m-thick seal (caprock and bedrock) units (Figure 2.2-1). The outer lateral boundary has a no-flow condition to represent a semi-closed system for the following two cases.

- 20-km-radius, representative of a relatively small basin
- 100-km-radius, representative of a relatively large basin

Here we introduce the concept of Active CO_2 Reservoir Management (ACRM), which involves engineering CO_2 and brine migration using a combination of CO_2 injection, brine extraction, and residual brine re-injection in saline aquifers. The processes and benefits of ACRM are similar to those of CO_2-based Enhanced Oil Recovery (CCS-EOR). In contrast, Passive CO_2 Reservoir Management is an approach wherein the migration of CO_2 and brine can only be controlled by the injection of CO_2. One of the aspects that ACRM has in common with CCS-EOR is the possibility of generating revenue from the extracted fluids; namely, fresh water produced via the desalination of brine, using technologies such as Reverse Osmosis (RO), which will generate residual (concentrated) brine. Thus, ACRM requires evaluation of disposal options for the residual brine, including reinjection. The combination of brine extraction and residual-brine reinjection with CO_2 injection enables a large reduction in fluid-pressure buildup, as well as a “push-pull-push” manipulation of the CO_2 plume. The goal is to manipulate the CO_2 plume in such a way that it exposes

- ***less*** of the caprock seal to CO_2, which, together with the reduction in fluid-pressure buildup will substantially reduce the vertical (upward) migration of CO_2, as well as CO_2-enriched brine and
- ***more*** of the primary storage aquifer to CO_2, with a greater fraction of the aquifer being utilized for trapping mechanisms.

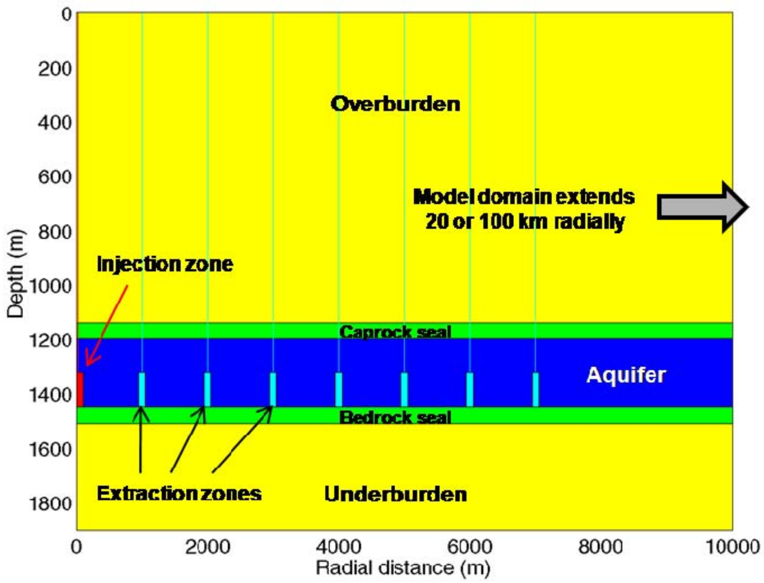


Figure 2.2-1. Conceptual model used in the modeling study.

Table 2.2-1. Hydrological properties applied to the CO_2-storage aquifer and (caprock and bedrock) seal units.

Property	Aquifer	Seals
Horizontal and vertical permeability (m^2)	10^{-13}	10^{-20} to 10^{-17}
Pore compressibility (Pa^{-1})	4.5×10^{-10}	4.5×10^{-10}
Porosity	0.12	0.12
van Genuchten (1980) *m*	0.46	0.46
van Genuchten a (Pa^{-1})	5.1×10^{-5}	5.1×10^{-5}
Residual CO_2 saturation	0.05	0.05
Residual water saturation	0.30	0.30

Figure 2.2-2 is an example of how CO_2-plume manipulation can achieve both of these important goals. Substantially less caprock is exposed and CO_2 is distributed vertically in a much more favorable configuration. Figures 2.2-3 and 2.2-4 show that ACRM can greatly reduce fluid-pressure buildup in the reservoir. Thus, ACRM is similar to CCS-EOR in that a combination of fluid injection and extraction can be used to control reservoir pressure and to improve *sweep efficiency*, thereby obtaining the best economic utilization of the reservoir resource. Results of the CO_2 reservoir modeling study by Buscheck et al. (2010) show that ACRM can provide the following benefits:

- Large increase in CO_2 storage capacity, with minimal pressure buildup
- Greater utilization of the aquifer resource for CO_2 trapping and storage
- Reduced migration of CO_2 resulting from reduced exposure of the caprock to CO_2, together with greatly reduced pressure buildup
- Greatly reduced migration of brine (virtually eliminated if the extraction ratio = 1)
- Large reduction in the Area of Review (Figure 5), which will reduce the scope and expense of site characterization and permitting activities
- If all CO_2 operations in a basin are actively managed, this facilitates:

- CO_2 and brine migration being unaffected by neighboring CO_2 operations, and vice versa
- assessing and conducting each CO_2 operation *independently*
- reducing the vulnerability of CCS performance to natural-system and conceptual-model uncertainties

- The possibility of Enhanced Water Recovery, to support Reverse Osmosis (RO) desalination

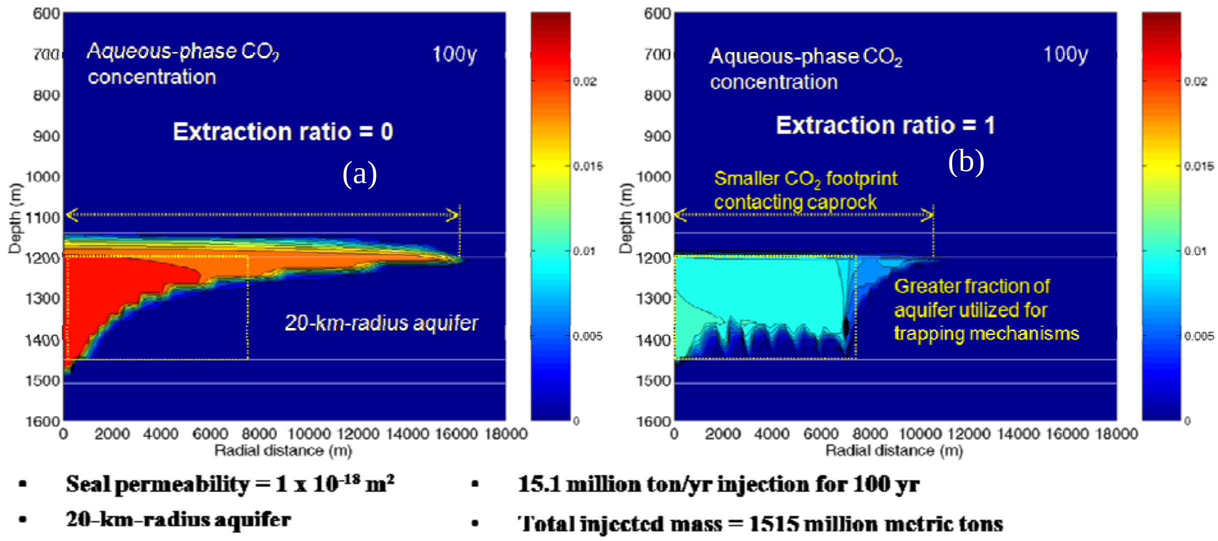


Figure 2.2-2. Contour of aqueous-phase CO_2 concentration ia plotted for (a) Passive CO_2 Reservoir Management and (b) Active CO_2 Reservoir Management. Note that the extraction ratio is defined to be the net extracted volume of brine (extraction minus reinjection) divided by the injected CO_2 volume.

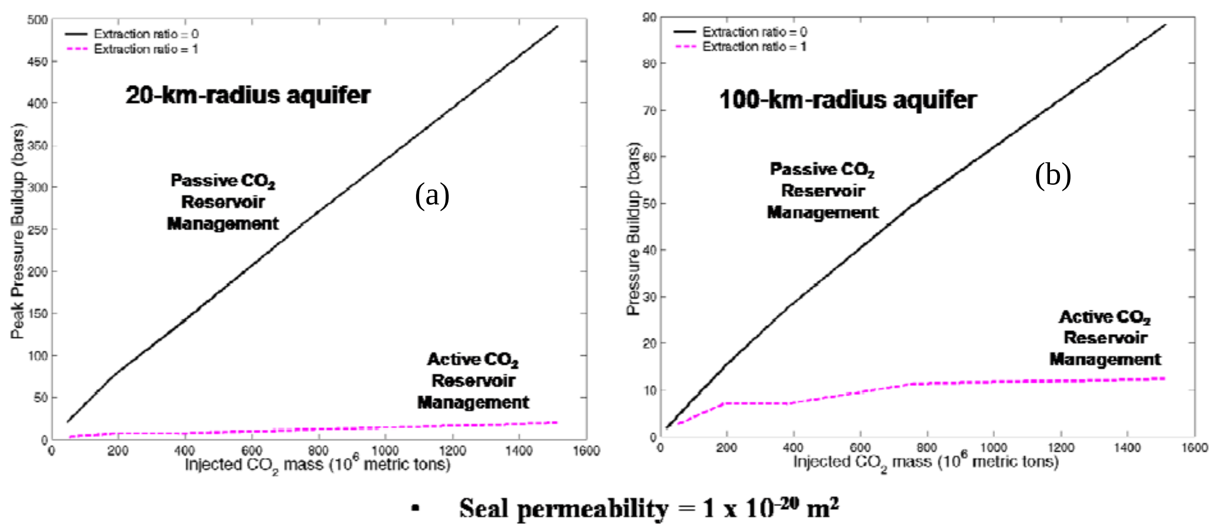
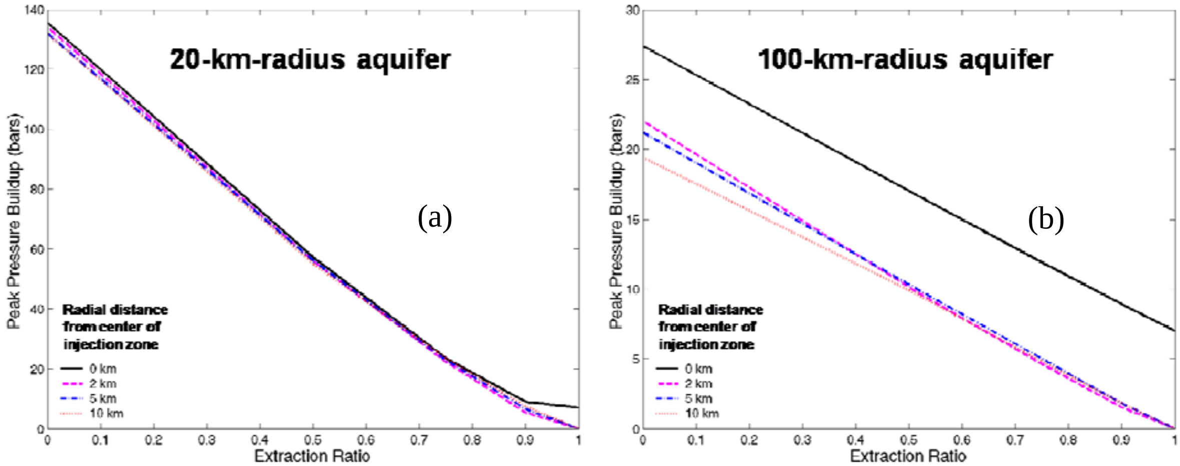
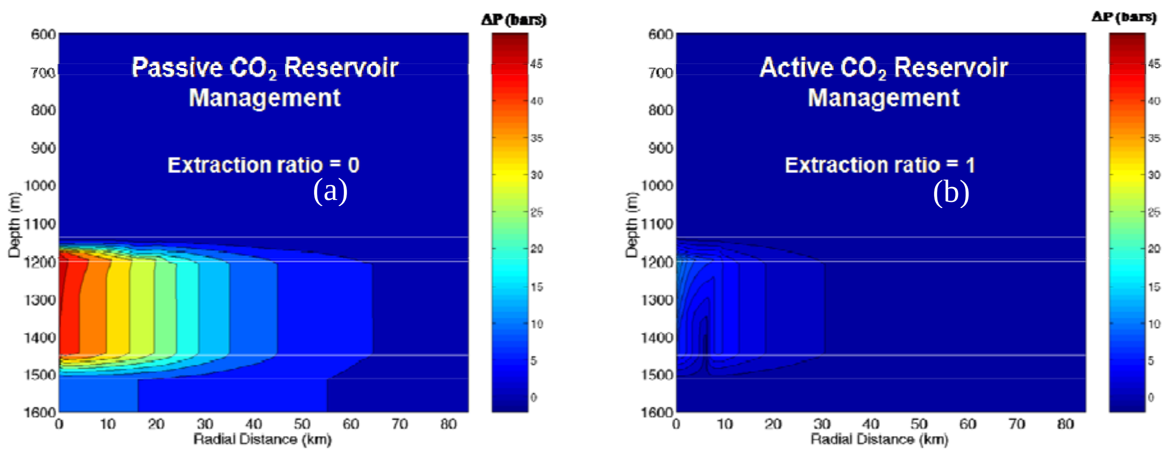


Figure 2.2-3. Peak injection-zone reservoir pressure buildup plotted as a function of injected mass of CO_2 for semi-closed aquifers with a radius of (a) 20 km and (b) 100 km. Plots are provided for both Passive CO_2 Reservoir Management and Active CO_2 Reservoir Management, which has an extraction ratio of 1. Note that the extraction ratio is defined to be the net extracted volume of brine (extraction minus reinjection) divided by the injected CO_2 volume.



- **Seal permeability = 1 x 10 20 m²**
- **No delay in extraction**
- **3.8 million ton/yr injection for 100 yr**
- **Total injected mass = 378 million metric tons**

Figure 4. Peak reservoir pressure buildup, at various distances from the center of the injection zone, plotted as a function of extraction ratio for semi-closed aquifers with a radius of (a) 20 km and (b) 100 km. Plots pertain to a total injected CO_2 mass of 378 million metric tons. Note that the extraction ratio is defined to be the net extracted volume of brine (extraction minus reinjection) divided by the injected CO_2 volume.



- **Seal permeability = 1 x 10 18 m²**
- **100-km-radius aquifer**
- **15.1 million ton/yr injection for 100 yr**
- **Total injected mass = 1515 million metric tons**

Figure 2.2-5. Contours of fluid-pressure buildup are plotted at the end of the injection period for (a) Passive CO_2 Reservoir Management and (b) Active CO_2 Reservoir Management (ACRM). Because the Area of Review (AOR) will be related to the spatial extent of fluid-pressure perturbation, the AOR will be much smaller for the ACRM.

3.0 Task 3: Injection and Reservoir Hazard Management: The Role of Injection-Induced Mechanical Deformation and Geochemical Alteration at In Salah CO_2 Storage Project

3.1 In Salah Storage Project Data Acquisition, Interpretation, and Information Exchange

LLNL participated in the Science Advisory Board review meeting in Cambourne, U.K., February 2 – 4, 2010. Summaries of our work pertaining to flow modeling, geomechanical response to injection, and geochemical/reactive transport modeling involving the near-wellbore environment were provided in oral and poster presentations.

In addition, LLNL and the JIP continued our monthly project status discussions during teleconferences.

3.2 Reactive Transport Studies

Geochemistry experiments designed to study injection of CO_2 at the wellbore environment under reservoir temperature and pressure conditions were completed during the quarter. Important reactions were determined through characterization formation (and cement) mineral assemblages in response to exposure to CO_2-saturated brine in addition to measuring associated changes in brine chemistry over time. With a complete data set consisting of data collected from experiments involving both sandstone and shale samples from the KB-502 core, we used geochemical modeling to determine reactive mineral phases and to quantify kinetic constants specific to the In Salah formation minerals. The modeling results of the experiments were used to further constrain our reactive transport model for CO_2 injection in the near-field wellbore environment.

The experimental data set consists of results for (1) reactions of the sandstone and shale core samples (as separate experiments) with a synthetic brine designed to mimic the composition of the In Salah brine, followed by injection of CO_2 and consequent reactions, and (2) hydration of anhydrous Class G cement calcium-silicon-aluminum oxides, followed by subsequent carbonation. Geochemical speciation modeling was used to glean insights into possible sets of reactions that could explain observed changes in brine chemistry in each of the experiments in addition to furnishing provisional reaction rates for use in reactive transport modeling. The modeling entailed assuming candidate mineral phases that could exist in the system, either as existing constituents of the formation mineralogy or as reaction product precipitates. For example, reactive minerals were assumed to include ankerite, a Ca-Fe carbonate cement phase present in the sandstone, chlorite, a clay mineral present in both the sandstone and shale materials, and illite clay present in the shale. Reaction products include amorphous SiO_2 (identified as a solid phase in the laboratory experiments), as well as kaolinite, gibbsite, and smectite clays (suspected solid phases in the laboratory experiments). Mineral dissolution and precipitation dissolution reactions were presumed to be driven by disequilibrium with the brine chemistry (e.g., as a result of the introduction of CO_2) and were modeling using either equilibrium or kinetic assumptions, as appropriate (Figure 1).

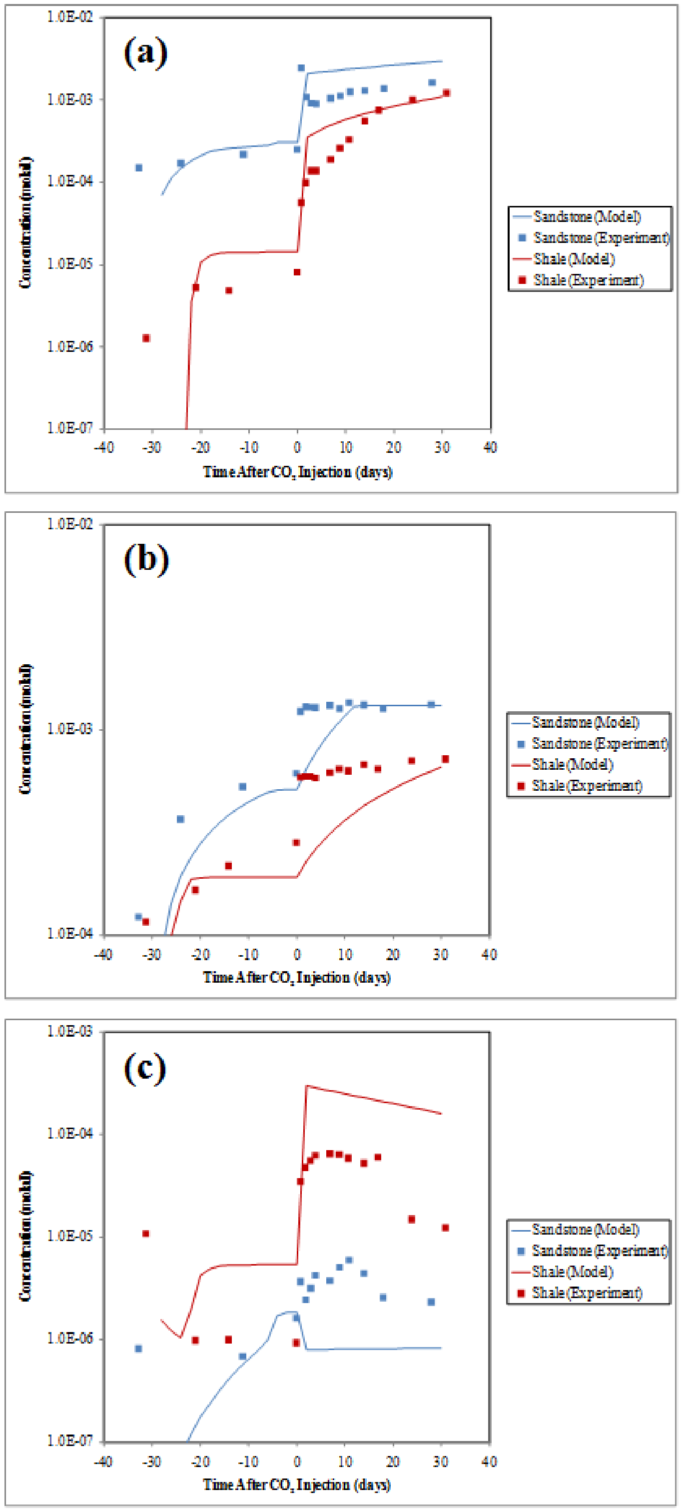


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Figure 1. Simulated and measured concentrations of (a) iron, (b) silicon, and (c) aluminum for the sandstone and shale core samples experiments as a function of time.

3.3 Geomechanical Studies

The geomechanical work continued in several areas. In previous quarters, the deformation of the overburden, resulting from the NUFT reservoir simulations, was predicted and compared with the InSAR data. In this quarter, we have been updating the geomechanical analysis with the latest NUFT results that incorporated the new permeability data (from the JIP) and the new STARS model.

Prior geomechanical analysis assumed a homogeneous elastic overburden. This modeling suggested that the land surface deformation is highly sensitive to the mechanical properties of the overburden. As such, we are currently incorporating a more detailed overburden model (e.g., seven layers) into our geomechanical response simulation. We are also currently extending the geomechanics simulations to the extended flow model encompassing injection into both KB-502 and KB-503 over a decade-long simulated injection period (refer to Task 4.0 status update, below).

Finally, with respect to the induced seismicity studies, communications with the JIP and technical partners have continued, as in the previous reporting period. To date, only baseline, pre-injection data have been available; consequently, simulations have not yet been performed.

3.4 Integration of Reactive Transport and Geomechanical Study Results for Field-scale Interpretation

LLNL received the most recent STARS model data set with interpreted permeability and porosity field for the reservoir in January 2010. This data set includes the extended geologic model, including the portion of the reservoir near KB-503. We have processed the STARS model data set and used the updated model to improve the geologic model implemented in LLNL's NUFT simulator. A geological model comparison between STARS and NUFT models is illustrated on Figure 2.

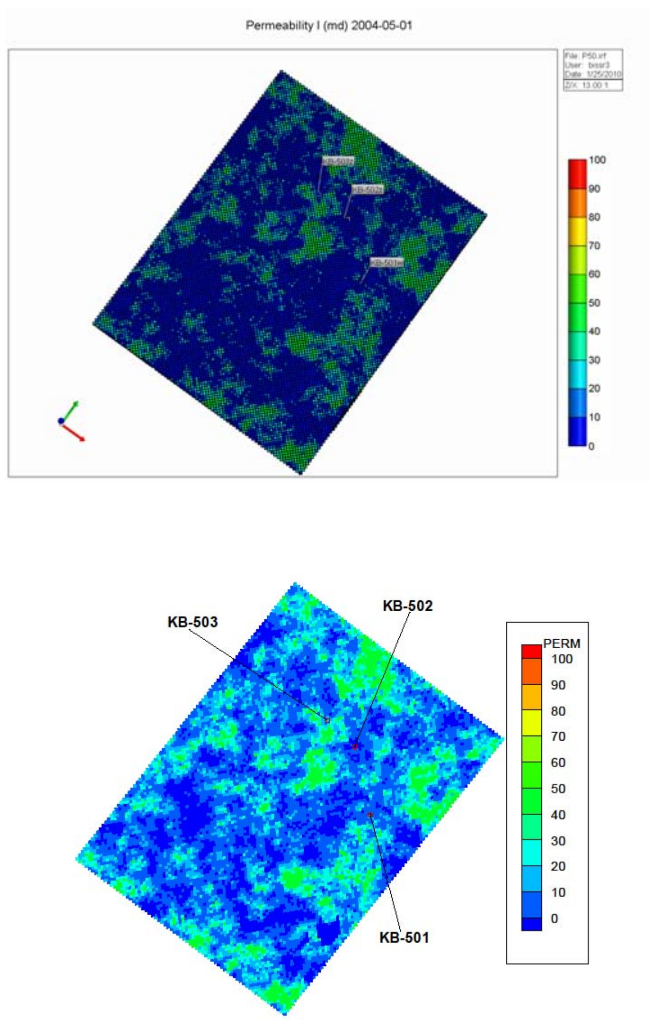


Figure 2: Comparison of permeability maps between STARS (top) and NUFT (bottom) models.

Based on the new geologic model, we have developed a revised NUFT simulation to model CO_2 injection at KB-502 and have calibrated the model via history matching to well bottom hole pressure (BHP) calculated by Prosper model. The NUFT simulation was run for a three-year period, including an 819-day injection period from April 2005 and to July 2007, followed by a 276-day post-injection period. The injection history profile and preliminary comparison of the BHP history predicted by NUFT model and by Prosper output are shown on Figures 3 and 4, respectively.

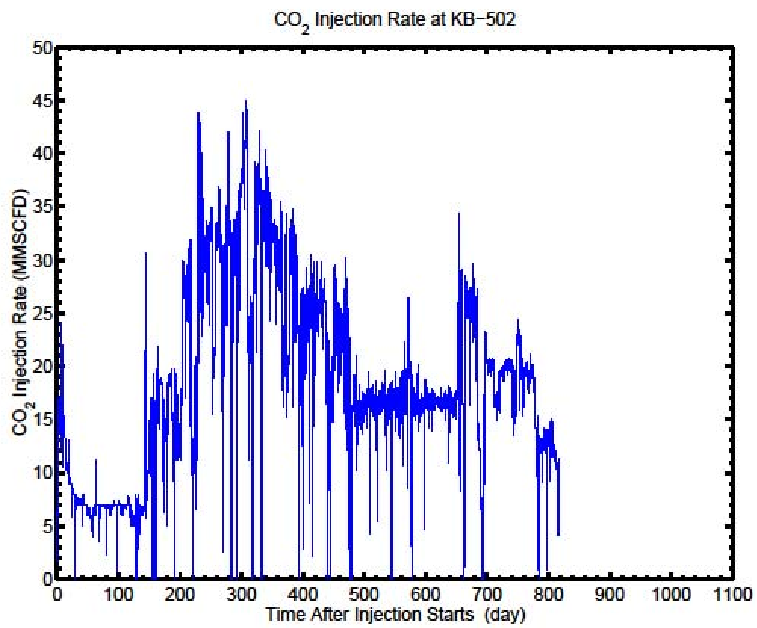


Figure 3: The CO_2 injection history at KB502.

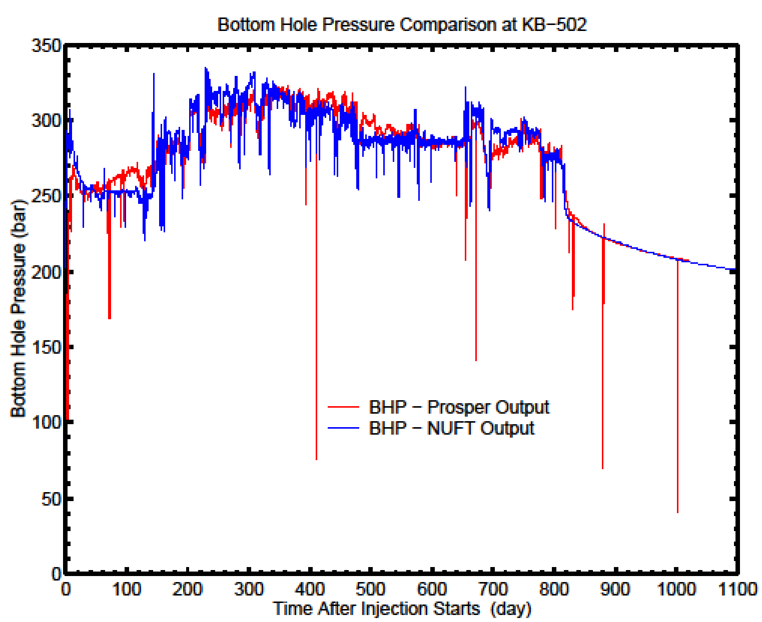


Figure 4: Bottom hole pressure comparison between NUFT simulation results and Prosper calculations.

4.0 Task 4: Carbon Sequestration Support to Collaborative Efforts in China

4.1 Technical Support for potential CCS project collaboration

Julio Friedmann travelled to China on April 13—23 to engage with Shenhua DCL co. The travel was coordinated with WVU (Jerry Fletcher and Qinyung Sun) and DOE-HQ (Mark Ackiewiecz). We met with Mr. Ren Xiangkun in Beijing, and also met with Mr. Wu and his staff on-site in inner Mongolia. The meeting included new Chinese team members, including Dr. Zhang Don (Peking Univ.) and Dr. Li (Inst. for Rock and Soil Sciences), who have agree to work with Shenhua and the US team and share additional geological, geophysical, petrophysical, and geochemical data.

4.2 Preliminary investigation of the Ordos Basin sequestration resource

No additional work since FY09.

4.3 Sequestration support

Construction of initial static geomodels, capacity estimates, hazard maps, wellbore integrity assessments, monitoring programs, and CO_2 injection program simulations will start in the 3rd quarter of FY10

4.4 Development of initial field program

None in the 2nd quarter

4.5 Reports and documents

None in the 2nd quarter

5.0 Task 5: Snøhvit CO_2 Storage Project: Understanding the role of injection-induced mechanical deformation and directed sea-floor monitoring

5.1 Geomechanical simulation and hazard management

We have just started work in this area and hired Dr. Laura Chiaramonte (Ph.D. Stanford) in February 2010. We are currently in the process of securing shared data and information from StatoilHydro and other sources (e.g., public domain) to develop a static geomodel of the Snøhvit injection site for use in all related applications. Given the geometry of major faults and fractures in and above the reservoir and estimates of the in-situ stresses, we will forecast the minimum change in effective stress needed to induce slip along portions of faults and predict hydromechanically induced deformation and fracturing of the caprock. These results will serve as the basis for seismic modeling for the prediction of microseismic signatures of the failure events.

5.2 Development of Seafloor Geochemical and Geophysical Monitoring Approaches

No work in 2nd Quarter

Deliverable Status: Green indicates completed deliverables, yellow indicates a change in deliverable due date, white indicates deliverables are on schedule.

Deliverable Number	Deliverable Description	Completion Date	WBS
1.1	Six White Papers submitted to NETL	November 15, 2009	1.1
1.2	Detailed Project Management Plan	Evolving effort driven by NETL; expected completion by July 30,2010.	1.2
2.1	Final Report on Brine Treatability Analysis	12 months from acceptance of funds	2.1
2.2	Final Report on Reservoir Pressure Analysis	12 months from acceptance of funds	2.2
2.3	Final Report on Brine Treatment Cost Analysis	12 months from acceptance of funds	2.3
3.1	Complete initial reactive transport simulations of wellbore integrity	December 31 2009	3.0
3.2	Complete integration of batch experiments and reactive transport calculations	March 31 2010	3.0
3.3	Provide progress update to BP of integration of geomechanical and geochemical analysis	9 months from acceptance of funds	3.0
3.4	Complete injection induced seismicity studies	12 months from acceptance of funds	3.0
4.1	Visit to Beijing to collect and share data from Shenhua DCL field efforts	April 23, 2010	4.0
4.2	Commence support for field pilot injection planning and design	6 months from acceptance of funds pending data from China	4.0
4.3	Commence simulation of preferred monitoring tool suite	9 months from acceptance of funds	4.0
4.4	Present results of preliminary pilot simulations to Shenhua DCL	12 months from acceptance of funds	4.0
5.1	Complete initial static geomodel	9 months from acceptance of funds	5.0
5.2	Provide progress update to StatoilHydro of geomechanical analysis	12 months from acceptance of funds	5.0

Significant Events

Task	Event	Date
1.0	Carroll gave an invited presentation on trace metal geochemistry in carbon sequestration environments for the American Chemical Society	March 21, 2010
2.0	Project review at the FY10 Strategic Center for Coal Mining Carbon Sequestration Peer Review	March 17, 2010
3.0	In Salah Science Advisory Board review meeting in Cambourne, U.K.	February 2 – 4, 2010
4.0	Julio Friedmann travelled to China to engage with Shenhua DCL co.	April 13 – 23, 2010
1.0, 3.0, 5.0	Hired Dr. Laura Chiaramonte	February 2010

Project Milestones

Title: 1.1 Complete edits on White Papers
Completed Date: November 15, 2009

Title: 1.2 Detailed project management plan
Extended Date: July 30, 2010

Title: 1.3 Identify natural analog of field site qualities
Completed Date: January 19, 2010

Title: 1.4 Identification of natural analog of field sites
Planned Date: November 15, 2010

Title: 1.5 Complete lab specific research for FY10
Planned Date: 12 months from acceptance of FY10 funds

Title: 2.1 Final Report on Brine Treatability Analysis
Planned Date: 12 months from acceptance of funds

Title: 2.2 Final Report on Reservoir Pressure Modeling
Planned Date: 12 months from acceptance of funds

Title: 2.3 Final Report on Brine Treatment Cost Analysis
Planned Date: 12 months from acceptance of funds

Title: 3.1 Initial reactive transport simulations of wellbore integrity
Planned Date: December 31, 2009

Title: 3.2 Integration of batch exp and reactive transport calcs
Planned Date: March 31, 2010

Title: 3.3 Update to BP of integration
Planned Date: 9 months from acceptance of funds

Title: 3.4 Complete injection induced seismicity studies
Planned Date: 12 months from acceptance of funds

Title: 4.1 Construction of static geomodel for preferred site
Planned Date: 12 months from acceptance of funds

Title: 4.2 Simulation of site fate and transport
Planned Date: 12 months from acceptance of funds

Title: 4.3 Assessment of potential MMV tools and methodologies
Planned Date: 12 months from acceptance of funds

Title: 5.1 Establish requirements for data and information exchange
Planned Date: May 6, 2010

Title: 5.2 Commence development of preliminary static geomodel
Planned Date: 6 months from acceptance of funds

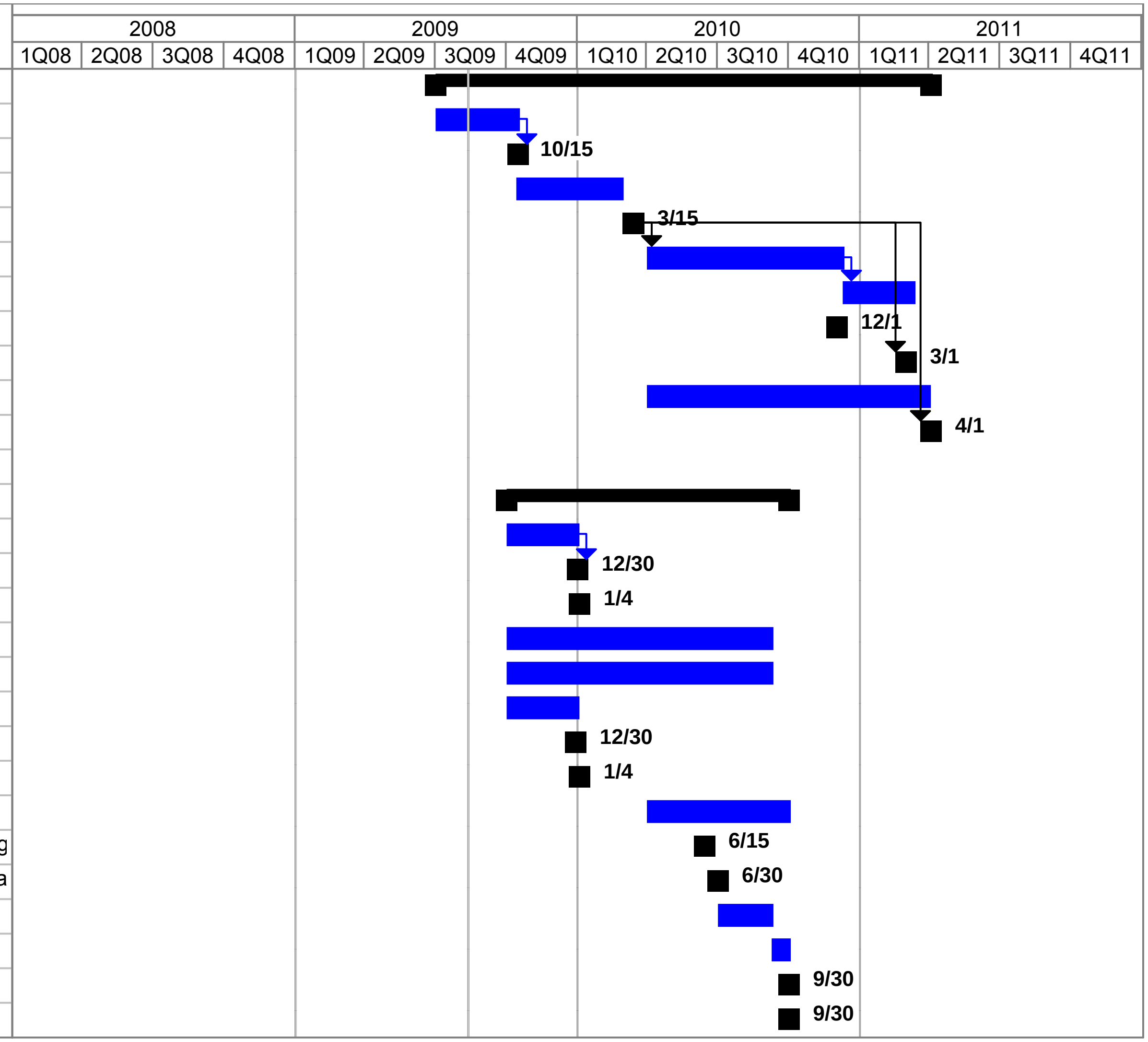
Title: 5.3 Commence initial simulations of hydromechanical deformation near injectors
Planned Date: 9 months from acceptance of funds

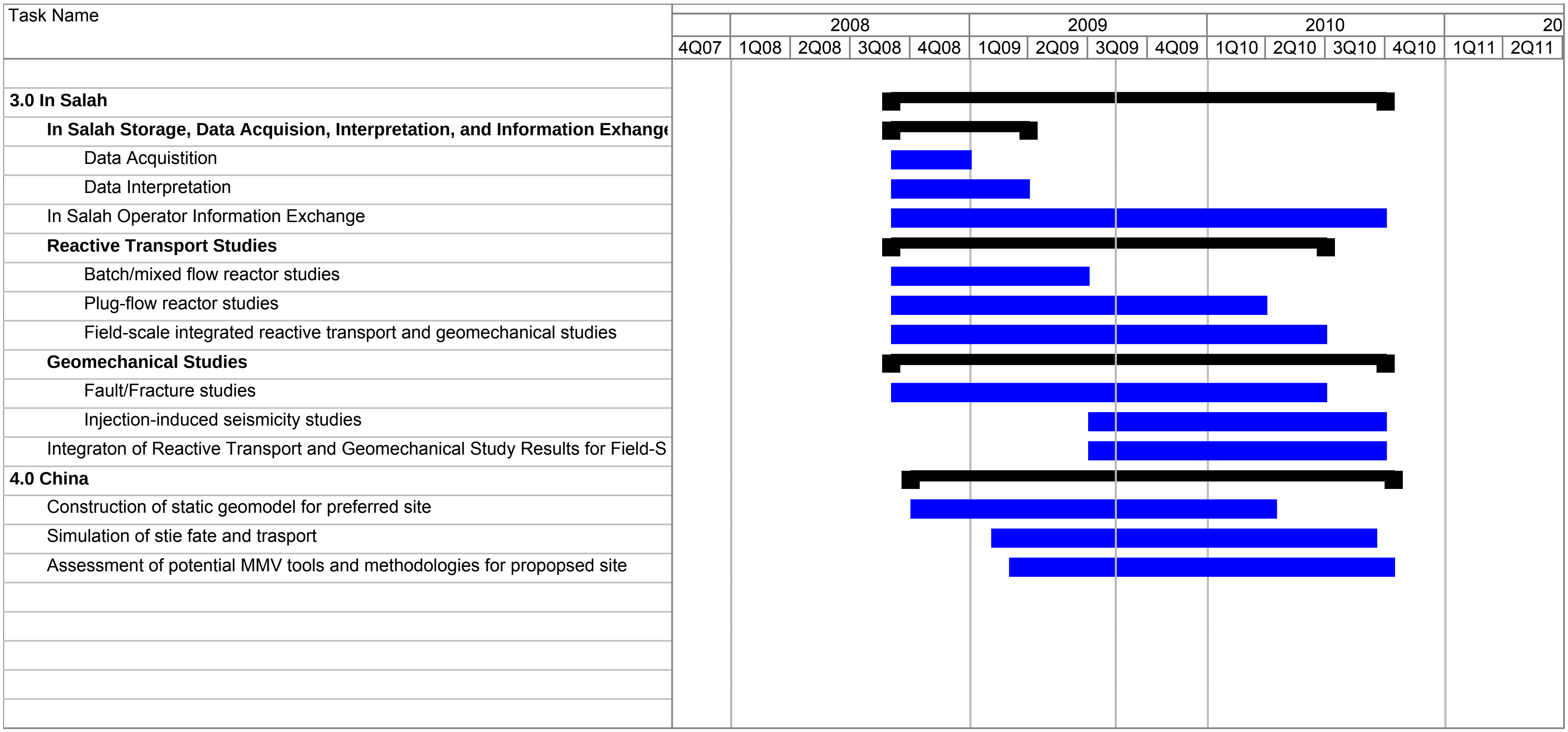
Title: 5.4 Initiate development of preliminary failure envelope calculations for fault networks
Planned Date: 12 months from acceptance of funds

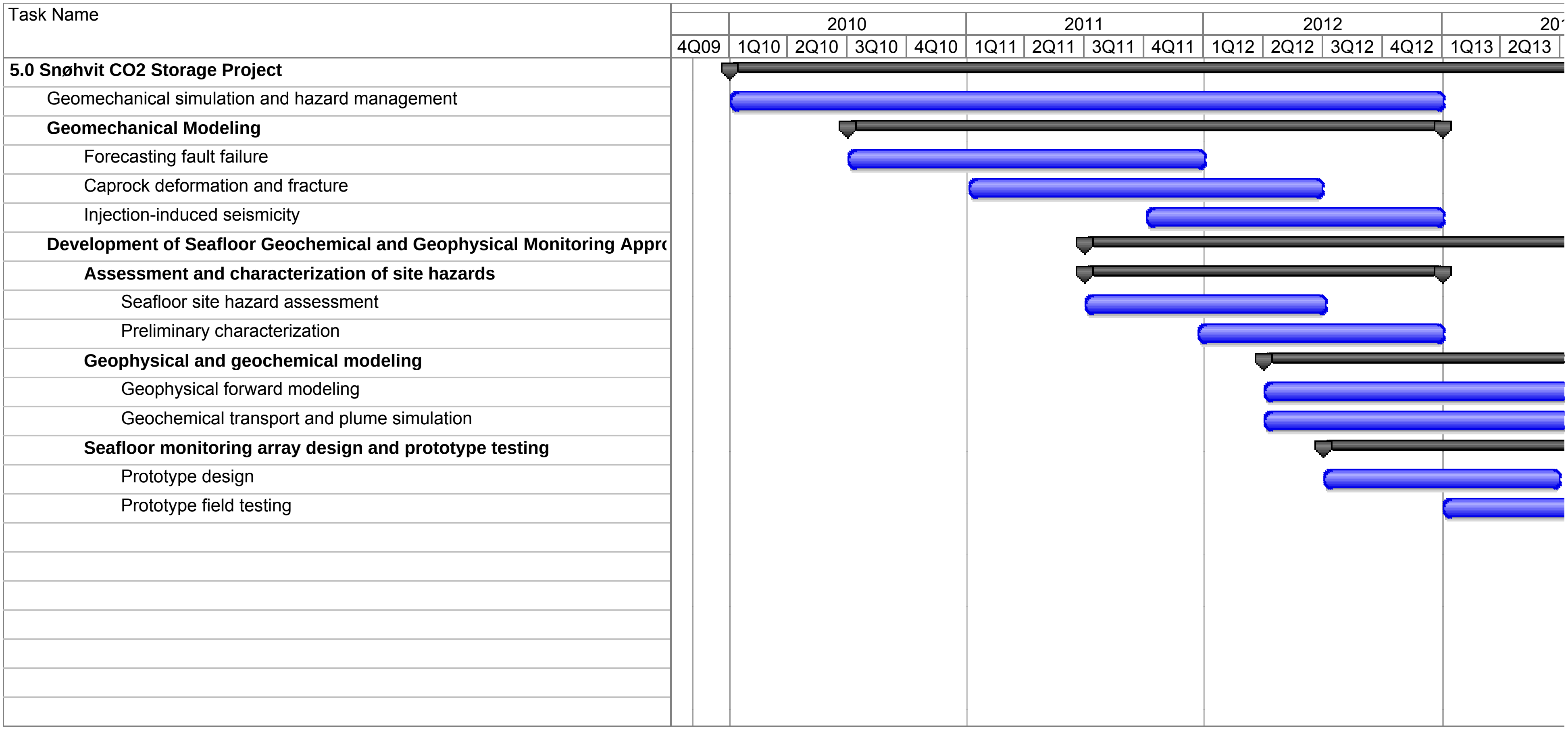
Carbon Sequestration Schedule (Baseline)

Note: See Deliverable status for schedule milestones variance explanations.

Task Name
1.0 Risk Assessment
Complete White Papers
Detailed Project Management Plan
Lab Specific Research
Acceptance of FY10 funds
Identify natural analog of field site qualities
Identification of natural analog of field sites
NRAP Semi-Annual report
NRAP workshop annual report
Lab Specific research
Final report presented at NRAP workshop
2.0 Freshwater-Brine treatment modeling and experiments
Incorporate rejection coefficient model in EQ3/6
Feeds to brine treatment modeling
Rejection coefficient capability complete
Brine treatment experiments
Reservoir Pressure Modeling
Incorporate pressure field modeling improvements to NUFT
Feeds to reservoir pressure modeling
NUFT software modifications complete
Negotiate field demonstration activity for FY11
Results to date from Reservoir Pressure Modeling to Brine Treatment Modeling
Results to date from Brine Treatment Modeling to Brine Treatment Cost Estima
Brine Treatment Cost Estimation
Prepare final report for submittal to NETL
Final report on Brine Treatment submitted to NETL
Final report on Reservoir Pressure Modeling submitted to NETL




Task Name
2008
2009
2010
20
4Q07
1Q08
2Q08
3Q08
4Q08
1Q09
2Q09
3Q09
4Q09
1Q10
2Q10
3Q10
4Q10
1Q11
2Q11
3.0 In Salah
In Salah Storage, Data Acquision, Interpretation, and Information Exchang
Data Acquistition
Data Interpretation
In Salah Operator Information Exchange
Reactive Transport Studies
Batch/mixed flow reactor studies
Plug-flow reactor studies
Field-scale integrated reactive transport and geomechanical studies
Geomechanical Studies
Fault/Fracture studies
Injection-induced seismicity studies
Integraton of Reactive Transport and Geomechanical Study Results for Field-S
4.0 China
Construction of static geomodel for preferred site
Simulation of stie fate and trasport
Assessment of potential MMV tools and methodologies for propopsed site


Task Name
2010
2011
2012
201
4Q09
1Q10
2Q10
3Q10
4Q10
1Q11
2Q11
3Q11
4Q11
1Q12
2Q12
3Q12
4Q12
1Q13
2Q13
5.0 Snøhvit CO2 Storage Project
Geomechanical simulation and hazard management
Geomechanical Modeling
Forecasting fault failure
Caprock deformation and fracture
Injection-induced seismicity
Development of Seafloor Geochemical and Geophysical Monitoring Appro
Assessment and characterization of site hazards
Seafloor site hazard assessment
Preliminary characterization
Geophysical and geochemical modeling
Geophysical forward modeling
Geochemical transport and plume simulation
Seafloor monitoring array design and prototype testing
Prototype design
Prototype field testing

Carbon Sequestration Budget

APL Area	PROJ_NAM	PROJ_LONG_NAM	PROJ_TASK_NO	PROJ_TASK_NAM	Values Prior Year Carryover	Current Year Funding	Total Funding Available	YTD Costs	Current Month Liens	Remaining Funding
Carbon Mgmt	LLNL CARBON SEQUESTRATION PGM	**CARBON SEQUESTRATION**	**TASK 1.0 NRAP**	Natl Risk Assessmnt	725,247.99	1,000,000.00	1,725,247.99	350,899.71	1,978.89	1,372,369.39
			TASK 2.0 FR WATER	Fresh Water Gen	137,181.63	600,000.00	737,181.63	269,605.95	31,026.46	436,549.22
			TASK 3.0 In Salah	In Salah CO2 Storage	432,640.90	500,000.00	932,640.90	394,843.49	2,107.81	535,689.60
			TASK 4.0 CS China	CS in China	408,548.64	550,000.00	958,548.64	99,641.36	11.30	858,895.98
			TASK 5.0 Snohvit	Snohvit CO2 Storage	0.00	300,000.00	300,000.00	0.00	0.00	300,000.00
	LLNL CARBON SEQUESTRATION PGM Total				**1,703,619.16**	**2,950,000.00**	**4,653,619.16**	**1,114,990.51**	**35,124.46**	**3,503,504.19**
Carbon Mgmt Total					**1,703,619.16**	**2,950,000.00**	**4,653,619.16**	**1,114,990.51**	**35,124.46**	**3,503,504.19**

Appendix

Table 3. Appendix Content

Task	Event	Type
1.0	NRAP white paper	Task 1 NRAPwhitepaperR3.pdf
1.0	Trace metal geochemistry in carbon storage environments	Task 1 ACS.pdf
2.0	Project review at the FY10 Strategic Center for Coal Mining Carbon Sequestration Peer Review	Task 2.pdf
3.0	In Salah Science Advisory Board review meeting in Cambridge, U.K.	Task 3a.pdf Task 3b.pdf